Radio Science at Jupiter: Past Investigations, Current Results, and Future Prospects

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***Abstract*—Over the last 40 years, several missions of the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have explored the largest planet in the solar system, Jupiter. Radio Science has been a key component of each mission to the planet, where radio signals between the spacecraft and the Earth-based observing antennas have been utilized to determine the physical properties of Jupiter and its moons, their atmospheres, ionospheres, and gravity fields. As a spacecraft passes through or around the Jovian system, small changes in phase, frequency, and amplitude of the radio signal are induced by the surrounding environment. These changes are detectable and form the basis for determining gravitational fields, planetary motion, and reconstruction of atmospheric and ionospheric profiles. The era of outer-planet exploration began in 1973 and 1974 with the Pioneer 10 and 11 flybys of Jupiter. Several missions have used Jupiter's massive gravitational well to perform a gravity assist to reach farther in the solar system, starting with Pioneer 11 in 1974 and Voyager 1 and Voyager 2 in 1979 with subsequent flybys from Ulysses in 1992, Cassini-Huygens in 2000, and New Horizons in 2007. Jupiter has hosted two dedicated orbiting spacecraft thus far: Galileo from 1995-2003 and Juno from 2016 to present. Throughout this time, instrumentation advances in both spacecraft technology and technology developed for ground stations have improved the precision and accuracy of the radiometric measurements, leading to improved results from radio science investigations. The latest mission to Jupiter, Juno, includes the most advanced radio science instrumentation to date. With Juno's unique polar orbit and dual frequency radio links, it is able to probe the planet's deep interior structure and zonal wind profile with measurements of the gravitational field and probe the electron densities in the Io plasma torus, a doughnut-shaped ring around Jupiter charged with particles emitted by the volcanic activity on Io. Upcoming missions, such as the planned NASA's Europa Clipper multiple flyby mission in 2022, potential follow-on Europa Lander, and the ESA's Jupiter Icy Moons Explorer mission in 2022, may make further strides in the study of the planet and its moons utilizing radio science.**

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1. INTRODUCTION

With a mass of 1.898×10^{27} kg (~317 Earth masses) and equatorial radius of 71,492 km, Jupiter is the largest planet in the solar system. As the first planet to be formed in the solar system, understanding Jupiter's composition, interior, and origin is essential to understanding how the solar system itself was formed. To learn about our giant neighbor, the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have sent nine spacecraft to Jupiter since the dawn of planetary robotic exploration.

In the early 1970s, NASA's Pioneer 10 and 11 spacecraft were the first to visit Jupiter. Pioneer 10 performed a flyby of Jupiter in 1973 followed by Pioneer 11 in 1974. The Voyager 1 and 2 spacecraft followed in 1979 in their grand tour of the solar system. It was understood that Jupiter's massive gravitational well could be used to slingshot spacecraft and increase or decrease their speed relative to the Sun. In 1992, ESA's Ulysses spacecraft performed a flyby of Jupiter en-route to the Sun. Cassini flew by en-route to Saturn in 2000 and New Horizons flew by en-route to Pluto in 2007. Jupiter was orbited by NASA's Galileo spacecraft from 1995-2003. The latest mission to Jupiter is NASA's Juno mission, which arrived in 2016 and expected to stay for a total of 32 science orbits until 2021. Figure 1 shows the orbital diagram of each mission to visit Jupiter.

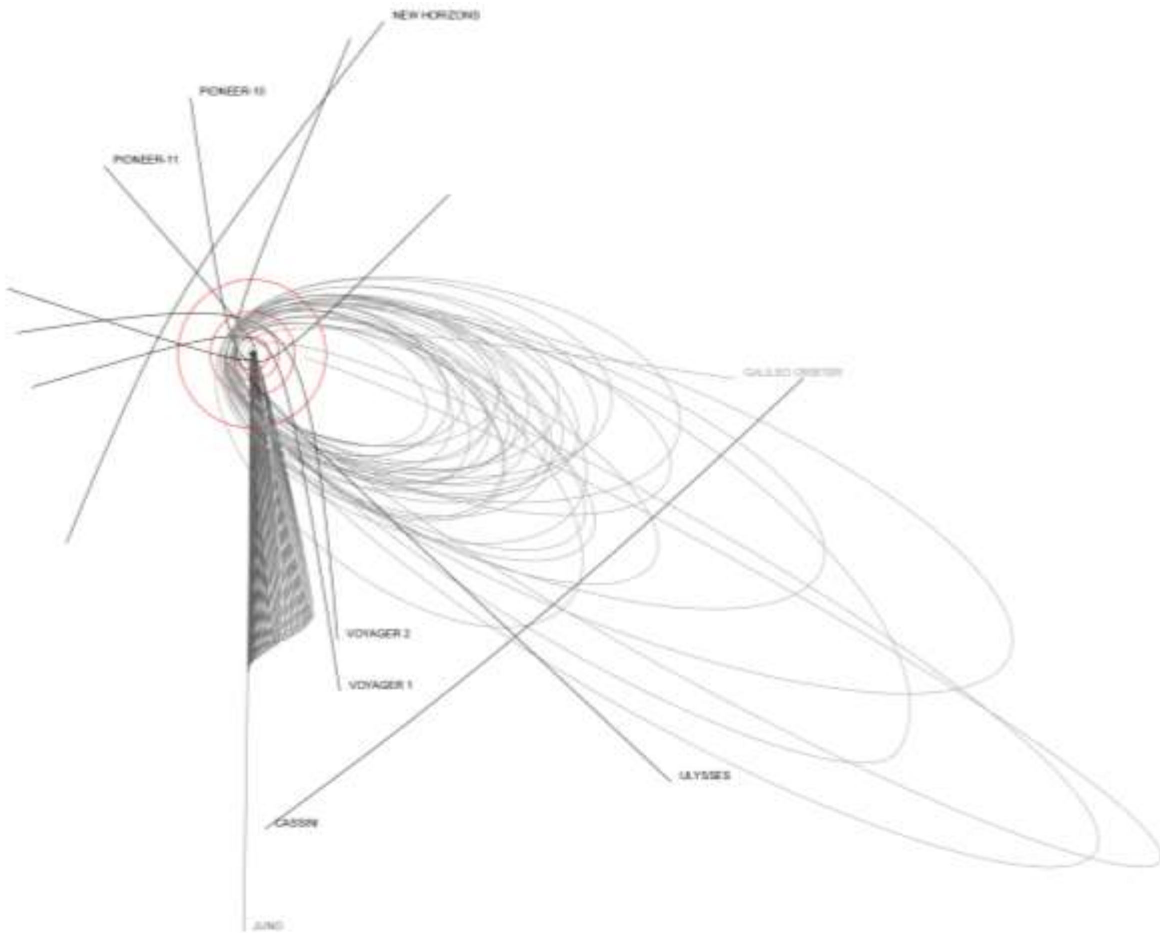

Figure 1. Orbital diagram of every planetary mission that visited Jupiter in the Ecliptic J2000 coordinate system. Shown in red are the orbits of the Galilean moons (Io, Europa, Ganymede, and Callisto). All orbital data used in this plot are publically available on the Planetary Data System NAIF website http://naif.jpl.nasa.gov

Radio Science has been a key instrument on every spacecraft that has visited Jupiter. Radio science utilizes the telecommunications link between the spacecraft and Earth-based receiving stations of NASA's Deep Space Network [1] or ESA's ESTRACK Network. Small changes in amplitude and/or phase of the radio link provide the scientific insight into:

- Atmospheres and Ionospheres with occultations of planetary bodies
- Charged particle distribution with occultations of torus, corona, etc.
- Interior properties with gravitational field determination
- Surface properties with occultations and bistatic scattering
- Celestial motion and relativistic effects
- In-Situ Doppler tracking of probes for wind profiles or landers for surface motion

Thus far, every mission that has visited Jupiter has utilized Radio Science in order to investigate the interior of Jupiter and the Galilean moons (Io, Europa, Ganymede, and Callisto), investigate the atmosphere and ionosphere of Jupiter and the Galilean moons, investigate the Io Plasma Torus in the magnetosphere, and to improve planetary and satellite ephemeris for science and navigational purposes.

This work is motivated by the scientific interest on Jupiter and its unique set of moons. Until Juno, nearly all of the radio science data from Jupiter has come from the 1970s. It is critical to compile the radio science instrumentation and radio science investigations from this era to not only inform current Juno radio science planning, but also for designing radio science instrumentation and operations concepts for upcoming missions

Three potential upcoming missions in the 2020s will make future strides in investigating Jupiter and its moons: NASA's Europa Clipper mission and potential follow-on Europa Lander, and ESA's Jupiter Icy Moons Explorer (JUICE). Radio Science is a beneficial addition to all three missions.

This paper begins by describing radio science instrumentation used in planetary science. Then, each science focus area is discussed in detail: Atmosphere & Ionosphere, Planetary Interior, and Planetary Magnetosphere. The paper concludes with a discussion on future work and missions to Jupiter in the context of Radio Science.

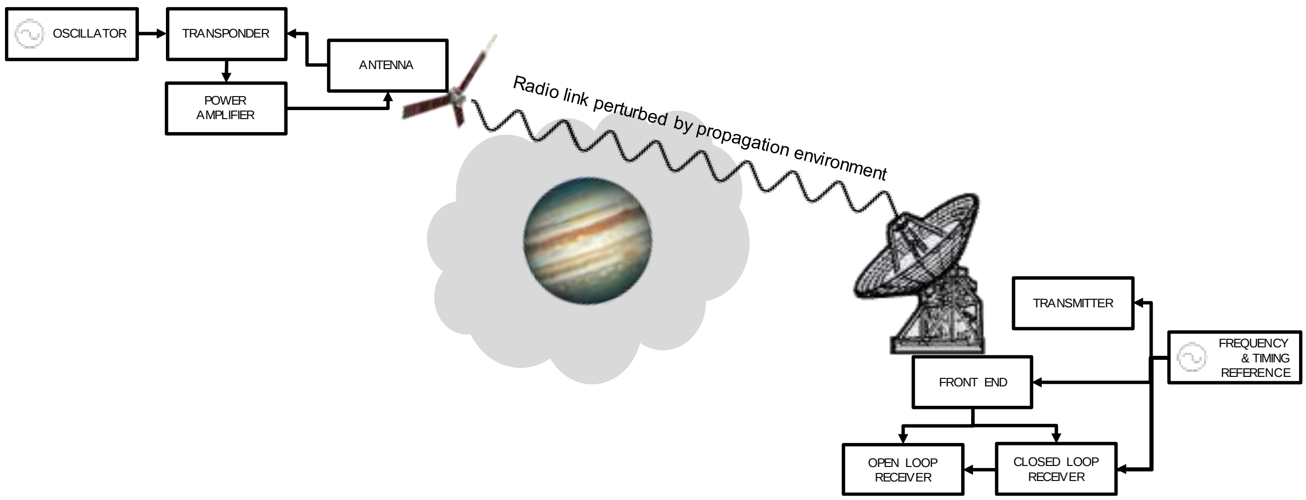

Figure 2. A generic Radio Science spacecraft-ground instrument.

2. Radio Science Instrumentation

In a general sense, Radio Science instruments may consist of a spacecraft communicating with an Earth-based ground station or two spacecraft communicating between each other. All missions to visit Jupiter have been single-spacecraft, thus the spacecraft-to-ground architecture is utilized as shown in Figure 2. In this architecture, there is a space element and a ground element.

At a minimum, the space element onboard the spacecraft will have a radio receiver, transmitter, or transponder for telecommunications. To improve frequency stability, a spacecraft may be equipped with a better onboard frequency reference, such as an Ultra Stable Oscillator (USO). The precision of the Radio Science measurement may also be improved through the use of multiple frequency bands. A linear combination of the frequency measured at two different bands significantly reduces or completely removes the noise caused by charged particles (e.g. emitted from the sun, trapped in a magnetosphere or ionosphere).

The ground element consists of a single or set of large aperture, mechanically stable antennas, such as those in NASA's Deep Space Network, ESA's ESTRACK Network, or radio astronomy antennas. A high precision frequency reference on the ground, such as a hydrogen maser, is used. When receiving the signal from the spacecraft, the entire spectrum may be recorded with open-loop receivers or Doppler, phase, and amplitude observables may be extracted in real time with a closed-loop receiver.

When the spacecraft generates the reference frequency, it is a *noncoherent* mode. Alternately, using its high-precision frequency reference, the ground station may uplink to the spacecraft, which receives the signal, multiplies it by a

Table 1. List of robotic planetary exploration spacecraft that have visited Jupiter and the respective Radio Science instrumentation and investigations.

Year	Mission	Type	Radio Science Instrumentation	RS Investigation
1973	Pioneer 10	Flyby	S-band Transponder	🟢 🔵 🟡(A)
1974	Pioneer 11	Flyby	S-band Transponder	🟢 🔵 🟡(A)
1979	Voyager 1	Flyby	Dual S- & X-band with USO	🟢 🔵 🟡(A)
1979	Voyager 2	Flyby	Dual S- & X-band with USO	🟢 🔵 🟡(A)
1992	Ulysses	Flyby	Dual S- & X-band Radio System	🟡(M)
1995	Galileo	Orbiter/Probe	S-band with Low Gain Antenna	🟢 🔵 🟡(I) 🟣
2000	Cassini	Flyby	*Triple S-, X-, & cross-link Ka-band with USO**	🔵
2007	New Horizons	Flyby	*X-band Transponder with USO and open-loop**	🔵
2016	Juno	Orbiter	Dual X- & Ka-band Links	🟢 🔵 🟡(M)
2020s	*Europa Clipper†*	*Orbiter*	*X-band and Ka-band Downlink Radio*	🟢 🔵
2020s	*Europa Lander†*	*Lander*	*X-band Radio*	🟢 🔵 🟣
2020s	*JUICE†*	*Orbiter*	*Dual/cross-link X- & Ka-band with USO*	🟢 🔵 🟡(A)

† Mission proposed/in-development, radio science investigations under study or proposed and may vary

** Instrumentation not used during flyby*

Gravity Science 🟢
Ephemeris/Celestial Mechanics 🔵
Atmosphere (A), Ionosphere (I), and /or Magnetosphere/Torus (M) Occultation 🟡
In-Situ Radio Science Observations 🟣

turnaround ratio, and phase coherently transmits it back to the ground. When the ground generates the reference frequency and receives the phase coherent signal back, it is a *coherent* mode. Radio occultations may be conducted in noncoherent mode with a USO frequency reference or in coherent mode; bistatic scattering experiments are conducted in noncoherent mode; and gravity science and celestial mechanics investigations are conducted in coherent mode.

As radio and planetary science technology have improved, instrumentation has greatly enhanced the results from Radio Science experiments at Jupiter. The Pioneer 10 and 11 were equipped with only S-band transponders [2]. Voyagers 1 and 2 improved by adding an X-band communications link and USO to improve frequency stability [3]. Ulysses utilized dual S- and X-band links during its flyby [4]. Galileo suffered a malfunction in the deployable high-gain antenna, requiring the use of the backup low-gain antenna at a single band, but still was able to use its onboard USO [5]. Cassini and New Horizons did not use their advanced Radio Science instrumentation during their flybys. Juno has the most advanced Radio Science instrumentation with dual X- and Ka-band links to map the gravitational field of Jupiter to high precision [6]. Table 1 shows a list of all planetary robotic spacecraft that have visited Jupiter, their respective radio science instrumentation, and the types of investigations done.

3. Investigations of the Atmosphere and Ionosphere

Radio occultation techniques are used to investigate planetary atmospheres and ionospheres by nearly every planetary mission, including those at Jupiter. In this geometry, the radio signal transmitted by a spacecraft becomes occulted by a celestial body (e.g. Jupiter or one of its moons) and is perturbed in phase as the radio signal path (ray path) through the atmosphere is bent by the atmosphere or ionosphere. The refractivity profile is produced by solving the Eikonal partial differential equation [7]:

$$(\nabla\phi)^2 = n^2 f^2 / c^2 \tag{1}$$

where ϕ is the spacecraft phase, n is the refractivity, f is frequency, and c is the speed of light. From the refractivity profile, the electron density in the ionosphere or temperature-pressure profile in the neutral atmosphere may be derived.

The first radio occultations of Jupiter were conducted by Pioneer 10 and Pioneer 11 in 1973 and 1974. Results of the atmosphere and ionosphere profiles [2] [8], although astonishing at the time, were later proved to be limited in scope by the data analysis method, which used a modified assumption of spherical symmetry (Abel transform), and limited instrumentation (S-band transponder with poor frequency reference was only able to probe to ~100 mbar pressure level).

Table 2. List of analyzed atmospheric and ionospheric occultations of Jupiter. The final column is the ID number of the occultation, which is the mission (P10/P11 = Pioneer 10 or 11; V1/V2 = Voyager 1 or 2; J*xx* = Galileo, where *xx* is the orbit number), and the occultation type (N = Ingress; X = Egress).

Date	Mission	Type	Lat	ID #
Dec 4, 1973	Pioneer 10	Ingress	28°N	P10N
Dec 4, 1973	Pioneer 10	Egress	58°N	P10X
Dec 3, 1974	Pioneer 11	Ingress	80°S	P11N
Dec 3, 1974	Pioneer 11	Egress	20°N	P11X
Mar 5, 1979	Voyager 1	Ingress	12°S	V1N
Mar 5, 1979	Voyager 1	Egress	~0°	V1X
Jul 10, 1979	Voyager 2	Ingress	66°S	V2N
Jul 10, 1979	Voyager 2	Egress	51°S	V2X
Dec 8, 1995	Galileo	Ingress	24°S	J00N
Dec 8, 1995	Galileo	Egress	43°S	J00X
Nov 8, 1996	Galileo	Ingress	28°S	J03N
Dec 21, 1996	Galileo	Ingress	23°S	J04N
Dec 21, 1996	Galileo	Egress	25°S	J04X

Both Voyager 1 and 2 were occulted by Jupiter in their 1979 flybys. The pair's identical radio instrumentation systems were equipped with dual S- and X-band transponders and a USO for frequency reference, much improved over the years since the Pioneer flyby. Data analysis techniques were advanced for ellipsoidal bodies such as Jupiter. Unfortunately, Voyager 2's ingress profile was unable to be analyzed due to significant horizontal refractivity variations resulting from the geometry of the occultation [3]. Voyager's radio occultation profiles still provide the best atmospheric temperature-pressure profiles of Jupiter's atmosphere to date. In addition to the atmospheric profiles, measurement of the radius of the 1-bar pressure level placed constraints on the interior properties of Jupiter.

Galileo conducted a series of Jupiter occultations during its time in orbit around Jupiter. However, due to the failure of the High Gain Antenna (HGA), the radio science capabilities of Galileo were greatly reduced. Instead of a dual-frequency link on the HGA, Galileo only had a single S-band link on the Low Gain Antenna at approximately 15 dB-Hz of signal-to-noise ratio. This made occultations of the atmosphere nearly impossible due to the attenuation and defocusing caused by the atmosphere. However, ionospheric occultations of Jupiter were possible and a total of 5 occultations were analyzed [9], bringing the total number of analyzed occultations of Jupiter to 13 as summarized in Table 2. Galileo also conducted a campaign of occultations of Io, Europa, Ganymede, and Callisto.

The ionosphere profiles from Voyager and Galileo are shown in Figure 3. Significant variations in the ionosphere are seen in the lower latitudes. Despite significant efforts in modeling the ionosphere, the characteristics of the electron density does

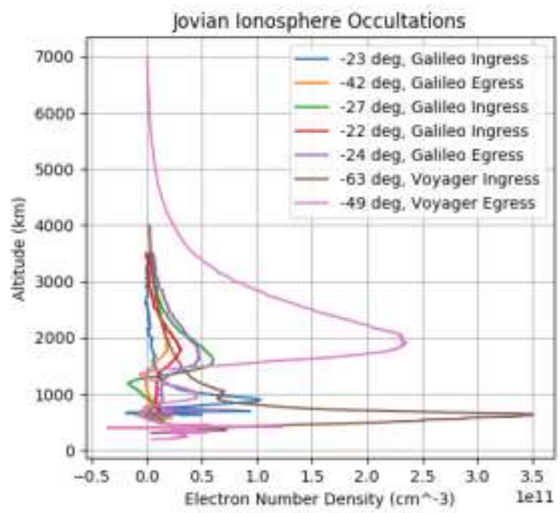

Figure 3. Ionosphere profiles obtained from Voyager and Galileo occultations (data from [9]).

not correlate with any obvious geophysical parameters (other than time of day) [10].

Jupiter's wind speed was measured by tracking the Doppler shift of the L-band (~1387 MHz) signal between Galileo and the atmospheric probe as it entered Jupiter's atmosphere. Consistent winds of up to 170 km/hr were measured at a depth of 4-20 bars. As the probe plunged deeper, there was no evidence that this wind speed was reduced [11]. The L-band signal was also intercepted at Earth-based observing sites (Very Large Array, Sorroco, New Mexico, United States, and Australia Telescope Compact Array, Narrabri, Australia) confirming the results from the orbiter link [12].

4. INVESTIGATIONS OF THE INTERIOR

Planetary gravity fields are closely related to the internal mass distribution of planets and satellites. As a consequence, the interiors of celestial bodies can be investigated with measurements of their gravitational potential U, which is typically represented by a spherical harmonic expansion as a function of radius r, latitude ϕ, and longitude λ [13]:

$$U = \frac{\mu}{r} - \frac{\mu^*}{r}\sum_{l=1}^{\infty}\left(\frac{a_e}{r}\right)^l P_l(\sin\phi)J_l + \frac{\mu^*}{r}\sum_{l=1}^{\infty}\sum_{m=1}^{\infty}\left(\frac{a_e}{r}\right)^l P_{lm}(\sin\phi)[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda] \quad (2)$$

where μ is the gravitational parameter, a_e is the reference radius (for Jupiter, a_e =71,492 km) and P_{lm} is the Legendre polynomial. The coefficients J_l represent the zonal harmonics and depend on latitude only. The coefficients C_{lm} and S_{lm} represent the tesseral and sectoral harmonics and depend on both latitude and longitude. A gravity field solution is produced by fitting the Doppler observables through a Square Root Information Filter to solve for the gravity coefficients, pole position, tidal parameters, spacecraft state vector and other parameters of interests.

If a planet is spinning with high angular velocity and in hydrostatic equilibrium, such as with Jupiter, the values of the even zonal harmonics (i.e. J_2, J_4, J_6…) will reflect the deformation of the fluid body due to fast uniform rotation. On the contrary, a hemispherical asymmetry, which identifies with odd zonal harmonics (i.e. J_3, J_5, J_7…), will bear information about differential rotation and dynamics of the visible zonal flows.

The Pioneer 10 and 11 spacecraft both flew by Jupiter providing the first estimate of the planet's low-degree even zonal harmonics [14] [15]. Later on, the Jupiter flybys of Voyager 1 and Voyager 2 improved the estimates for J_2, J_4 and J_6 [16], indicating no substantial deviation from the gravity field of a uniformly rotating fluid body. As a result, fluctuations of the mass distribution from differential rotation and asymmetric flows were thought to be small and the majority of post-Voyager Jupiter interior models assumed rigid body rotation. Nevertheless, observations of the surface atmospheric dynamics raised questions about the depth of the zonal winds, which are differentially rotating. A proposed theory envisaged co-axial cylinders extending throughout the interior of the planet and rotating with different angular velocities [17]. However, the gravity measurements from the Pioneer and Voyager missions were not accurate enough to discriminate between the two models.

The Galileo mission did not provide much improvement on Jupiter's gravity field due to poor orbital geometry for radio science investigations, but resolved low-degree harmonics and ephemeris of Galilean satellites through several flybys. Under the assumption of hydrostatic equilibrium, gravity measurements revealed that Europa's interior is differentiated with a combined thickness for ice and water shell of 80-170 km [18], ~5-10% of the moon's radius. Estimates of the ice shell thickness alone is estimated to be between a few kilometers to tens of kilometers thick based on modeling and measurement of the impact craters [19]. Ganymede, the largest satellite in the solar system, also appeared to be differentiated to some extent [20], whereas Callisto, the farthest of the four Galilean moons, is most likely an undifferentiated mixture of ice and rock [21].

Decades after the last Voyager flyby, the knowledge of Jupiter's gravity field dramatically improved with Juno's first two science orbits (labeled as PJ01 and PJ02) in late 2016. Although neither perijove was targeted as a gravity pass, the determination of the gravity field of the planet improved by a factor of 5 in comparison to previous published measurements [22] [23] and also provided the first estimate for J_8. The unprecedented accuracy allowed establishment of tighter constraints on the core mass and radial density distribution of Jupiter. A class of models involving a diluted core was proposed, capable of reconciling the predicted and

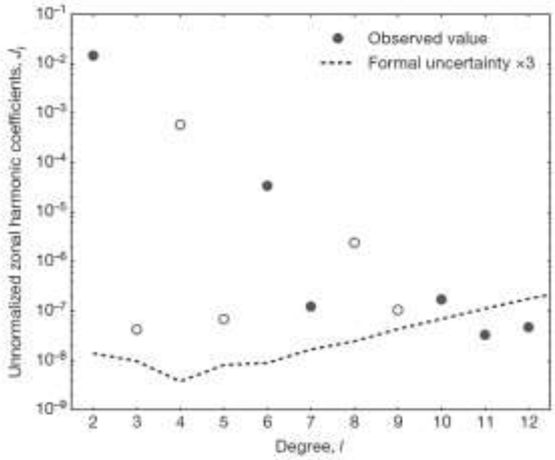

Figure 4. Estimate of Jupiter's zonal harmonics up to degree 12. Positive values are denoted with a filled circle and negative values with empty circles. The odd harmonics J_3, J_5 and J_7 are clearly above the 3-sigma uncertainty line and suggest the presence of an asymmetry between the hemispheres (from [25]).

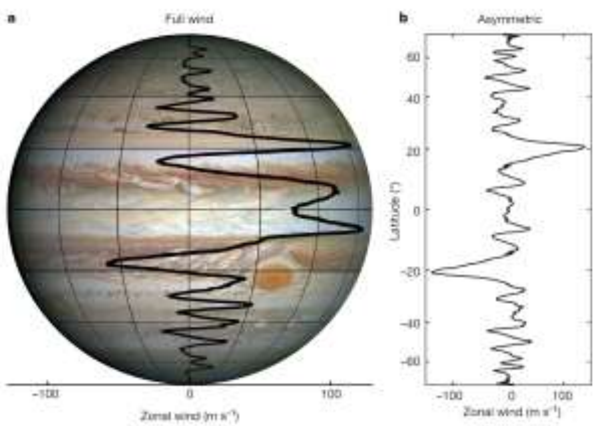

Figure 5. Correlation between the asymmetric gravity anomaly (left) and the wind profile (right) (from [26]).

observed values [24]. In this analysis, the core expands further out than previously thought with heavy elements dissolved into the hydrogen and helium envelope.

A turning point for the investigation of the interior of Jupiter was the completion of the first two Juno passes dedicated to gravity science, PJ03 and PJ06. The high-precision Doppler tracking of the spacecraft allowed for the reduction of the uncertainties on the even zonals, and more importantly, for the detection of non-zero odd harmonics J_3, J_5 and J_7, indicating a clear asymmetric signal between the hemispheres, as shown in Figure 4 [25].

As uniform rotation cannot account for a north-south asymmetry in the gravity field, the estimated odd zonals are necessarily related to differential rotation and Jupiter's strong zonal flows. This correlation between the asymmetric gravity anomaly and the wind profile is shown in Figure 5. The magnitude of the estimated odd harmonics holds information about the vertical depth of the surface zonal winds, which appear to decay exponentially along co-axial cylinders with a scale height of about 3,000 km [26], making up for about 1% of Jupiter's total mass.

The inversion of gravity data is, by definition, non-unique, meaning that several different interior models can produce the same external gravitational potential. However, in the era of Juno, one accredited model for Jupiter's structure is that of a planet with a diluted core extending out for a good fraction of the planet's radius. The deep interior is uniformly rotating whereas the zonal flows extend down below the surface and are suppressed at depth larger than a few thousands kilometers.

5. INVESTIGATIONS OF THE MAGNETOSPHERE

Interaction between Jupiter's magnetosphere and Io plays a significant role in shaping the magnetic field. The Jovian magnetosphere sweeps up gas and dust from Io's atmosphere, generated from volcanic activity on the surface. These particles originated from Io are ionized and trapped by the magnetic field into the Io Plasma Torus (IPT). Emission from these particles has been observed from ground-based telescopes and ultraviolet instruments of flyby missions including Pioneer and Voyager. A dispersive Doppler measurement (Δf), derived from spacecraft-to-Earth radio links, is sensitive to the electron content in the IPT [27]:

$$\Delta f = f_X - f_{Ka}\left(\frac{f_{D,X}}{f_{D,Ka}}\right) \tag{3}$$

where f_X is the X-band received frequency, f_{Ka} is the Ka-band received frequency, and the ratio $f_{D,X}/f_{D,Ka}$ is the ratio of transmitted X-band and Ka-band frequencies from the spacecraft.

The signature of the IPT was first detected in Voyager radio communications data but not analyzed from a scientific perspective. In 1992, the Ulysses flyby of Jupiter conducted the first Io Plasma Torus occultation [28]. Recently, the Juno mission provided another opportunity for radio occultations of the IPT during each perijove flyby as shown in Figure 6 [29]. Phipps et al. modeled and analyzed the IPT electron content during Juno's Perijove-1 gravity science pass [30], as shown in Figure 7. The findings improve the understanding of plasma properties of Io torus and improve the model of IPT electron density distributions.

6. FUTURE INVESTIGATIONS

As of the time of this publication, Juno has completed just over half of the prime mission's 32 orbits around Jupiter. As Juno continues to fly around Jupiter, the orbital plane will precess around the planet with respect to the direction to the Sun and project more of the spacecraft Doppler shift into the

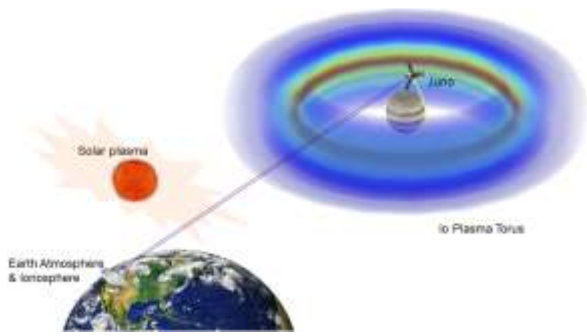

Figure 7. Geometry of an Io Plasma Torus occultation (not to scale), showing sources of dispersive noise on the radio link between the spacecraft and the ground.

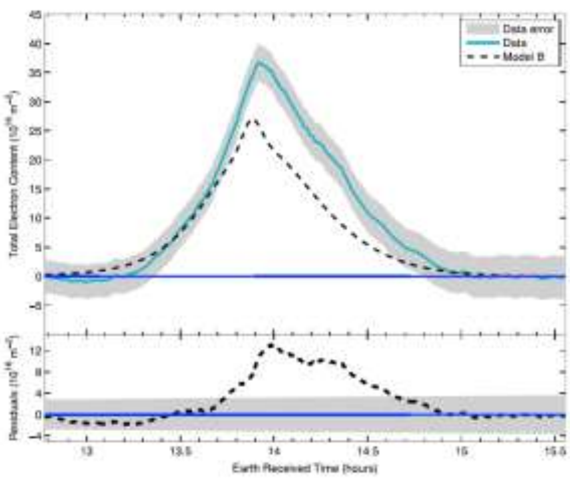

Figure 6. Comparison of observed differential Doppler (expressed as Total Electron Content) between X- and Ka-band downlinks during Juno's Perijove 1. It is compared to the Voyager-era model of the Io Plasma Torus (from [30]).

Earth direction. With more velocity projected onto the radio link, the sensitivity to Jupiter's gravity field will increase [31]. Juno will also measure tidal variations on the planet caused by the Galilean moons and Jupiter's moment of inertia from the precession of the pole as Jupiter orbits around the Sun [6]. Both precession and tidal variations provide crucial constraints on the interior properties of Jupiter, which help in explaining the existence of a core. Additionally, Juno will make more passes over the Great Red Spot, in which a gravity anomaly may be detectable [32].

There are several missions either under development or proposed to further investigate Jupiter and its unique set of moons. Radio Science is a key instrument on each of the proposals, providing future insights on the interior structure of the Galilean moons and Jupiter's atmosphere.

NASA's upcoming Europa Clipper mission may measure tidal perturbations to the gravity field of Europa during flybys to detect a subsurface ocean [33]. This would be accomplished by measuring the Doppler shift of the radio link from the spacecraft to the Deep Space Network during flybys. The potential follow-on lander, currently under study by NASA, may measure the local dynamic variability of the surface and lander through tracking of the Doppler shift between the lander and Earth, or a relay spacecraft [34].

The 3GM experiment onboard ESA's Jupiter Icy Moons Explorer (JUICE) will probe the gravity fields of Ganymede with an orbital phase and of Callisto with several flybys. The research for subsurface water reservoirs on the largest moons of Jupiter stands out among the main science objectives of the radio science experiment. Furthermore, the JUICE spacecraft will also perform an extended campaign of Jupiter occultations [35], with more than a hundred observation opportunities to probe the ionosphere and atmosphere of the planet.

7. CONCLUSION

With the nine spacecraft that have visited Jupiter in the past 40 years, Radio Science has played a key role in major discoveries in the atmospheres, ionospheres, and interior structure of the planet and moons. The Pioneer, Voyager, and Galileo missions measured the atmospheric and ionospheric structure of both Jupiter and the Galilean moons with radio occultations.

Juno has made major strides since the Pioneer era in investigating the interior properties of Jupiter by measuring its gravitational field. Through high precision X- and Ka-band radio systems, Juno has detected an asymmetric gravity field on Jupiter, which implies the zonal winds on Jupiter extend 3,000 km in depth.

Originally detected by Voyager, Ulysses and Juno have provided critical data in understanding the electron density structure in the Io Plasma Torus, a key component of Jupiter's magnetosphere.

NASA's upcoming Europa Clipper mission, potential follow on Europa lander, and ESA's upcoming JUICE mission will provide future insights into the Jovian system with Radio Science. A primary objective of the Europa Clipper and JUICE missions is to use gravity science to investigate the interior properties of the moons of Jupiter, which may provide detection of a liquid subsurface ocean – a key component required for life.

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The decision to implement the Europa Lander mission will not be finalized until NASA's completion of the National

Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

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